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Search for Scalar Diphoton Resonances in the Mass Range 65 – 600 GeV with the ATLAS Detector in pp Collision Data at $\sqrt{s} = 8 \text{ TeV}$

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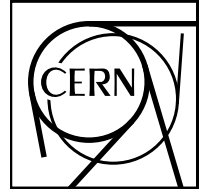
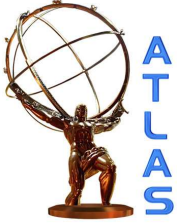
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 $\sqrt{s} = 8$ TeV**

The ATLAS Collaboration

Abstract

A search for scalar particles decaying via narrow resonances into two photons in the mass range 65–600 GeV is performed using 20.3 fb^{-1} of $\sqrt{s} = 8$ TeV pp collision data collected with the ATLAS detector at the Large Hadron Collider. The recently discovered Higgs boson is treated as a background. No significant evidence for an additional signal is observed. The results are presented as limits at the 95% confidence level on the production cross-section of a scalar boson times branching ratio into two photons, in a fiducial volume where the reconstruction efficiency is approximately independent of the event topology. The upper limits set extend over a considerably wider mass range than previous searches.

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In July 2012, the ATLAS and CMS collaborations reported the discovery of a new particle [1, 2] whose measured couplings and properties are compatible with the Standard Model Higgs boson (H) [3–6]. However, several extensions to the Standard Model, in particular models featuring an extended Higgs sector [7–13], predict new scalar resonances below or above the H mass which may be narrow when their branching ratio to two photons is non-negligible.

This Letter presents a search for a scalar particle X of mass m_X decaying via narrow resonances into two photons. It extends the method developed for the measurement of the H couplings in the $H \rightarrow \gamma\gamma$ channel [3] to the range $65 < m_X < 600$ GeV. Analytical descriptions of the signal and background distributions are fitted to the measured diphoton invariant mass spectrum $m_{\gamma\gamma}$ to determine the signal and background yields. The result is presented as a limit on the production cross-section times the branching ratio $BR(X \rightarrow \gamma\gamma)$, restricted to a fiducial volume where the reconstruction efficiency is approximately independent of the event topology. The resonance with mass m_X is considered narrow when its intrinsic width is smaller than $0.09 \text{ GeV} + 0.01 \cdot m_X$. This upper limit is defined such that the bias in the number of fitted signal events is kept below 10%, and ensures that the diphoton invariant mass width is dominated by the experimental resolution in the ATLAS detector. Model-dependent interference effects between the resonance and the continuum diphoton background are not considered.

The ATLAS detector [14] at the LHC [15] covers the pseudorapidity [16] range $|\eta| < 4.9$ and the full azimuthal angle ϕ . It consists of an inner tracking detector covering the pseudorapidity range $|\eta| < 2.5$, surrounded by electromagnetic and hadronic calorimeters and an external muon spectrometer.

The search is carried out using the $\sqrt{s} = 8$ TeV pp collision dataset collected in 2012, with stable beam conditions and all ATLAS subsystems operational, which corresponds to an integrated luminosity of $\mathcal{L} = 20.3 \pm 0.6 \text{ fb}^{-1}$ [17]. The data were recorded using a

diphoton trigger that required two electromagnetic clusters with transverse energies E_T above 20 GeV, both fulfilling identification criteria based on shower shapes in the electromagnetic calorimeter. The efficiency of the diphoton trigger [18] is $(98.7 \pm 0.5)\%$ for signal events passing the analysis selection.

The event selection requires at least one reconstructed primary vertex with two or more tracks with transverse momenta $p_T > 0.4$ GeV, and at least two photon candidates with $E_T > 22$ GeV and $|\eta| < 2.37$, excluding the barrel/endcap transition region of the calorimeter, $1.37 < |\eta| < 1.56$.

Photon reconstruction is seeded by clusters of electromagnetic calorimeter cells. Clusters without matching tracks are classified as unconverted photons. Clusters with matched tracks are considered as electron candidates, but are classified as converted photons if they are associated with two tracks consistent with a $\gamma \rightarrow e^+e^-$ conversion process, or a single track leaving no hit in the innermost layer of the inner tracking detector. The photon energy calibration procedure is the same as in Ref. [3].

Photon candidates are required to fulfill identification criteria based on shower shapes in the electromagnetic calorimeter, and on energy leakage into the hadronic calorimeter [19]. Identification efficiencies, averaged over η , range from 70% to above 99% for the E_T range under consideration. To further reduce the background from jets, the calorimeter isolation transverse energy E_T^{iso} is required to be smaller than 6 GeV, where E_T^{iso} is defined as the sum of transverse energies of the positive-energy topological clusters [20] within a cone of size $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ around the photon candidate. The core of the photon shower is excluded, and E_T^{iso} is corrected for the leakage of the photon shower into the isolation cone. The contributions from the underlying event and pile-up are subtracted using the technique proposed in Ref. [21] and implemented as described in Ref. [22]. In addition, the track isolation, defined as the scalar sum of the p_T of the primary vertex tracks with

$p_T > 1$ GeV in a $\Delta R = 0.2$ cone around the photon candidate, excluding the conversion tracks, is required to be smaller than 2.6 GeV.

The $m_{\gamma\gamma}$ invariant mass is evaluated using the leading photon (γ_1) and subleading photon (γ_2) energies measured in the calorimeter, the azimuthal angle $\Delta\phi$ and the pseudorapidity $\Delta\eta$ separations between the photons determined from their positions in the calorimeter and the position of the reconstructed diphoton vertex [3].

After selection, the data sample consists of a continuum background with dominantly $\gamma\gamma$, γ -jet, jet-jet events and Drell-Yan (DY) production of electron pairs where both electrons are misidentified as photons. Two peaking backgrounds arise from the Z boson component of the DY and from $H \rightarrow \gamma\gamma$.

To increase the sensitivity, the search is split into two analyses: a categorized low-mass analysis covering the range $65 < m_X < 110$ GeV, and an inclusive high-mass analysis covering $110 < m_X < 600$ GeV. To provide sidebands on both sides of the tested mass point m_X , the $m_{\gamma\gamma}$ ranges are wider than the m_X ranges probed and overlap at the transition between the two analyses.

The low-mass analysis requires a precise modeling of the DY background, dominated by the Z boson resonance, where both electrons are misidentified as photons, mostly classified as converted photons. The loss of signal sensitivity is mitigated by separating the events into three categories with different signal-to-background ratios, according to the conversion status of the photon pair: two unconverted (UU), one converted and one unconverted (CU) or two converted photons (CC). Table I shows the fractions of signal and DY events expected in each category.

TABLE I. Number of diphoton events in data (N_{data}), number of expected Drell-Yan events (N_{DY}), fractions of expected signal (f_X) and Drell-Yan (f_{DY}) in each conversion category for the low-mass analysis. The signal fraction is given for $m_X = 90$ GeV but the mass-dependence is negligible.

| $\gamma\gamma$ category | UU | CU | CC |
|-------------------------|----------------|----------------|----------------|
| N_{data} | 272184 | 253804 | 63224 |
| N_{DY} | 1080 ± 260 | 3400 ± 600 | 2700 ± 250 |
| f_{DY} | 15.0% | 47.3% | 37.7% |
| f_X | 48.7% | 42.5% | 8.8% |

In each category, the Z resonance shape is described by a double-sided Crystal Ball function [23]. Due to the limited size of the fully simulated $Z \rightarrow ee$ sample [24, 25] where both electrons are misidentified as photons, the shape parameters are determined by a fit to a dielectron data sample, where both electrons are required to fulfill shower shape identification criteria and the same E_T thresholds as the photons.

Since most of the electrons misidentified as photons underwent large bremsstrahlung, the invariant mass distribution of the Z boson reconstructed as a photon pair

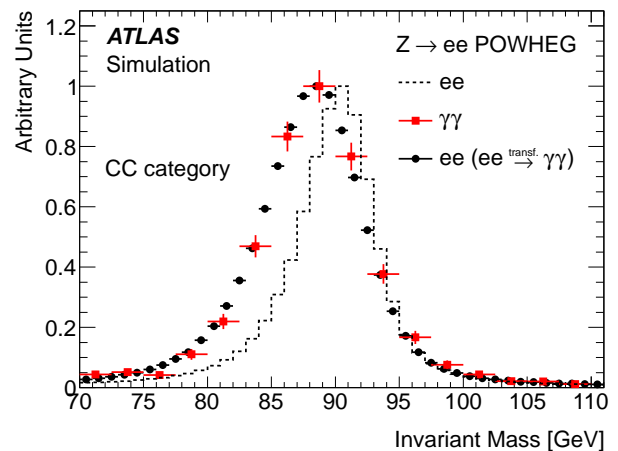


FIG. 1. Invariant mass distributions in the CC category for fully simulated $Z \rightarrow ee$ events reconstructed as ee (dotted-lines), reconstructed as $\gamma\gamma$ (squares), and reconstructed as ee after transforming the electrons to match the kinematics of the electrons misidentified as converted photons (circles).

is wider and shifted to lower masses by up to 2 GeV with respect to the Z boson mass reconstructed as an electron pair. The $Z \rightarrow ee$ invariant mass distributions extracted from data in each category are transformed by applying E_T -dependent shifts and smearing factors to the electron E_T and ϕ , to match the kinematics of the electrons misidentified as photons. Two sets of transformations are derived for γ_1 and γ_2 depending on their conversion status, using a $Z \rightarrow ee$ sample generated with POWHEG [26, 27] interfaced with PYTHIA8 [28] for showering and hadronization. Figure 1 illustrates the effect of the electrons' transformations on the invariant mass shapes in the fully simulated $Z \rightarrow ee$ sample. Systematic uncertainties on the template shapes and the Z peak position are evaluated by varying the parameters of the electrons' transformations by $\pm 1\sigma$.

The DY normalization is computed from the $e \rightarrow \gamma$ fake rates, defined as the ratios of $e\gamma$ to ee pairs measured in $Z \rightarrow ee$ data, separately for γ_1 and γ_2 and each conversion status. A correction factor obtained from fully simulated $Z \rightarrow ee$ events is applied to account for additional effects, mainly the differences in isolation efficiencies and vertex reconstruction efficiency between $\gamma\gamma$ and ee events. The associated uncertainties (9 to 25%) are dominated by the subtraction of the continuum background and the detector material description.

The determination of the analytical form of the continuum background and the corresponding uncertainties follow the method detailed in Ref. [1]. The sum of a Landau distribution and an exponential distribution is used over the full $m_{\gamma\gamma}$ range. The bias on the signal yield induced by the analytical shape function is required to be lower than 20% of the statistical uncertainty on the fitted sig-

nal yield for the background-only spectrum. This bias is measured from a large sample generated from a parameterized detector response, and is accounted for by a mass-dependent uncertainty. Figure 2 shows background-only fits to the data in the low-mass analysis for the three conversion categories.

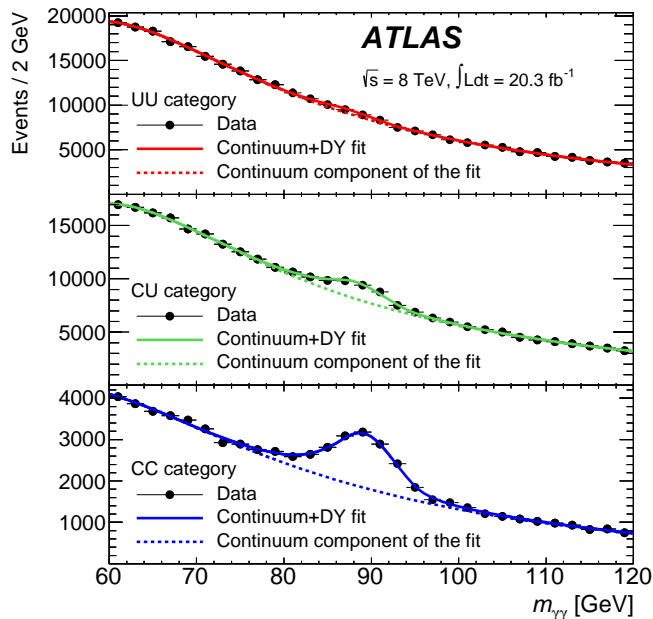


FIG. 2. Background-only fits to the data (black dots) as functions of the diphoton invariant mass $m_{\gamma\gamma}$ for the three conversion categories in the low-mass range. The solid lines show the sum of the Drell–Yan and the continuum background components. The dashed lines show the continuum background component only.

In the high-mass analysis, relative cuts $E_T^{\gamma 1}/m_{\gamma\gamma} > 0.4$ and $E_T^{\gamma 2}/m_{\gamma\gamma} > 0.3$ are added to the selection requirements to reduce the continuum backgrounds and thereby increase the signal sensitivity. In total, 108654 events with $100 < m_{\gamma\gamma} < 800$ GeV are selected.

To determine the continuum background shape over this large mass range, an exponential of a second-order polynomial is fitted inside a sliding $m_{\gamma\gamma}$ window of width $80 \cdot (m_X - 110) / 110 + 20$ GeV, centered on the mass point m_X . The analytical shape and the fit window width are chosen to fulfill the signal yield bias criterion, as defined for the low-mass analysis, to minimize the statistical uncertainty on the background.

The H background shape is modeled by a double-sided Crystal Ball function, and normalized for $m_H = 125.9$ GeV [29][30] using the most up-to-date Standard Model cross-section calculations and corrections [31] of the five main production modes: gluon fusion (ggF), vector-boson fusion (VBF), Higgs-strahlung (WH, ZH), and associated production with a top quark pair ($t\bar{t}H$). The ggF and VBF samples [3] are simulated with the POWHEG generator interfaced with PYTHIA8. The WH ,

ZH and $t\bar{t}H$ samples [3] are simulated with PYTHIA8. Figure 3 shows background-only fits to the data in the high-mass analysis.

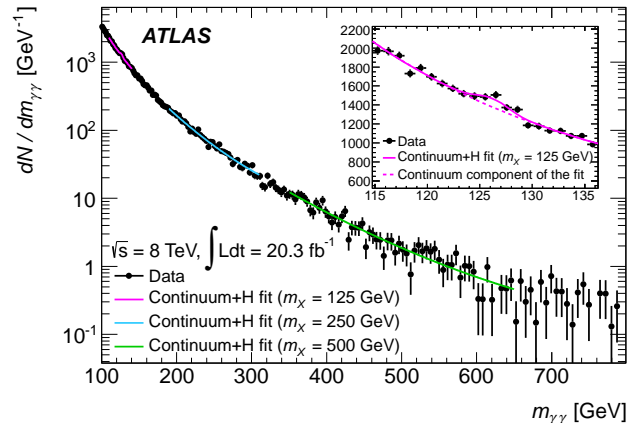


FIG. 3. Background-only fits to the data (black dots) as functions of the diphoton invariant mass $m_{\gamma\gamma}$ for the inclusive high-mass analysis. The solid line shows the sum of the Higgs boson and the continuum background components. The dashed line shows the continuum background component only.

The expected invariant mass distribution of the narrow resonance signal X is also modeled with a double-sided Crystal Ball function in the mass range $65 \leq m_X \leq 600$ GeV, using fully simulated $ggF(X)$ samples generated as for H , where H is replaced by a scalar boson with a constant width of 4 MeV. Polynomial parameterizations of the signal shape parameters as a function of m_X are obtained from a simultaneous fit to all the generated mass points m_X , separately for the high-mass analysis and the three low-mass analysis categories. The signal shape parameters extracted from $ggF(X)$ are compared to the other production modes $VBF(X)$, WX , ZX and $t\bar{t}X$; the bias on the signal yield due to the choice of $ggF(X)$ shape is negligible. The systematic uncertainty on the signal shape due to the photon energy resolution uncertainty ranges from 10% to 40% as a function of m_X [3]. The systematic uncertainty on the X peak position due to the photon energy scale uncertainty is 0.6% [3].

The fiducial cross-section $\sigma_{\text{fid}} \cdot BR(X \rightarrow \gamma\gamma)$ includes an efficiency correction factor C_X through

$$\sigma_{\text{fid}} \cdot BR(X \rightarrow \gamma\gamma) = \frac{N_{\text{data}}}{C_X \cdot \mathcal{L}} \quad \text{with} \quad C_X = \frac{N_{\text{MC}}^{\text{reco}}}{N_{\text{MC}}^{\text{fid}}},$$

where N_{data} is the number of fitted signal events in data, $N_{\text{MC}}^{\text{reco}}$ the number of simulated signal events passing the selection criteria and $N_{\text{MC}}^{\text{fid}}$ the number of simulated signal events generated within the fiducial volume. The fiducial volume, defined from geometrical and kinematical constraints at the generated particle level, is optimized to reduce the model-dependence of C_X using fully simulated samples of the five X production modes to cover

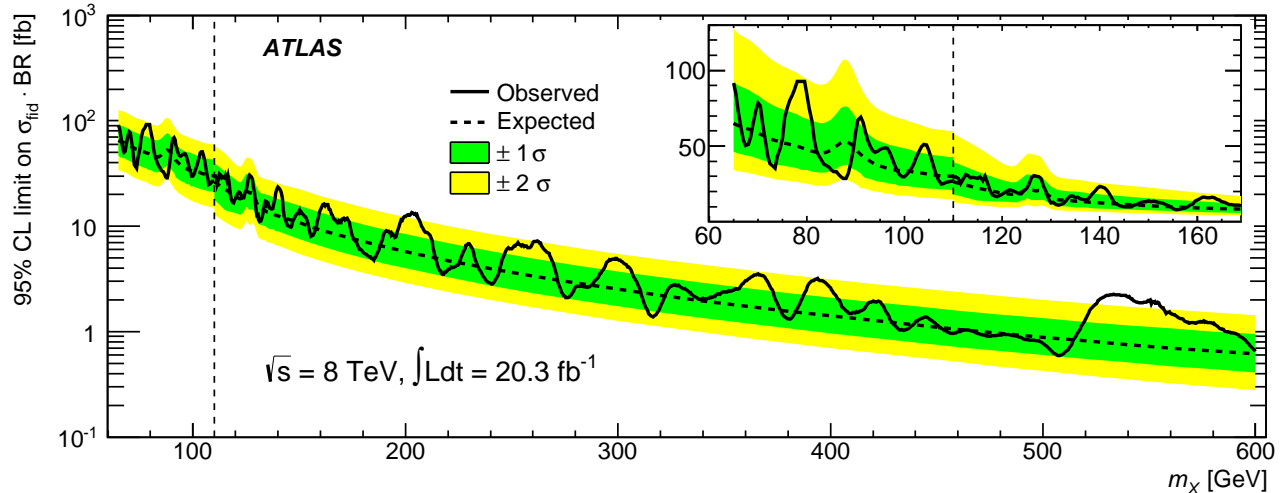


FIG. 4. Observed and expected 95% CL limit on the fiducial cross-section times branching ratio $BR(X \rightarrow \gamma\gamma)$ as a function of m_X in the range $65 < m_X < 600$ GeV. The discontinuity in the limit at $m_X = 110$ GeV (vertical dashed line) is due to the transition between the low-mass and high-mass analyses. The green and yellow bands show the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties on the expected limit. The inset shows a zoom around the transition point.

a large variety of topologies. The photon selection at generation level is similar to the selection applied to the data: two photons with $E_T > 22$ GeV and $|\eta| < 2.37$ are required; for m_X greater than 110 GeV, the relative cuts $E_T^{\gamma 1}/m_{\gamma\gamma} > 0.4$ and $E_T^{\gamma 2}/m_{\gamma\gamma} > 0.3$ are imposed. The particle isolation, defined as the scalar sum of p_T of all the stable particles (except neutrinos) found within a $\Delta R = 0.4$ cone around the photon direction, is required to be less than 12 GeV. The C_X factor is parameterized from the $ggF(X)$ samples, and ranges from 0.56 to 0.71 as a function of m_X . Systematic uncertainties include the maximum difference between the C_X of the five production modes, the effect of the underlying event (U.E.) and pile-up.

The statistical analysis of the data uses unbinned maximum likelihood fits. The DY and H shapes and normalizations are allowed to float within the uncertainties. In the low-mass analysis, a simultaneous fit to the three conversion categories is performed. Only two excesses with 2.1σ and 2.2σ local significances above the background are observed over the full mass range 65–600 GeV, for $m_X=201$ GeV and $m_X=530$ GeV respectively. This corresponds to a deviation of less than 0.5σ from the background-only hypothesis. Consequently, a 95% limit on $\sigma_{\text{fid}} \cdot BR(X \rightarrow \gamma\gamma)$ is computed using the procedure of Ref. [1]. The systematic uncertainties listed in Table II are accounted for by nuisance parameters in the likelihood function. In the low-mass analysis, the dominant uncertainties are the DY normalization and the residual topology dependence of C_X . In the high-mass analysis, the largest uncertainties arise from the energy resolution and the theoretical uncertainty on the production rate of the Standard Model Higgs boson around 126 GeV.

TABLE II. Summary of the systematic uncertainties

| | | | |
|---|-------------|---------------------------------|----------|
| <i>Signal and Higgs boson yield</i> | | <i>Z component of Drell-Yan</i> | |
| Luminosity | 2.8% | Normalization ^b | 9–25% |
| Trigger | 0.5% | Peak position ^b | 1.5–3.5% |
| γ identification ^a | 1.6–2.7% | Template shape ^b | 1.5–3% |
| γ isolation ^a | 1–6% | <i>Higgs boson background</i> | |
| Energy resolution ^{ab} | 10–40% | Cross-section ^c | 9.6% |
| <i>Signal and Higgs boson peak position</i> | | Branching ratio | 4.8% |
| Energy scale | 0.6% | <i>C_X factor</i> | |
| Continuum $\gamma\gamma$, γj , jj , DY | | Topology ^a | 3–15% |
| Signal bias ^a | 1–67 events | Pile-up & U. E. ^a | 1.4–3.2% |

^a mass-dependent.

^b category-dependent.

^c factorization scale + PDF uncertainties [31].

The observed and expected limits, shown in Fig. 4, are in good agreement, consistent with the absence of a signal. The limits on $\sigma_{\text{fid}} \cdot BR(X \rightarrow \gamma\gamma)$ for an additional scalar resonance range from 90 fb for $m_X=65$ GeV to 1 fb for $m_X=600$ GeV. These results extend over a considerably wider mass range than the previous searches by the ATLAS and CMS collaborations [1, 35], are complementary to spin-2 particles searches [36, 37], and are the first such limits independent of the event topology.

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